Habitable Planet Formation in Multiple-Star Systems

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ABSTRACT

Nearly a quarter of all known extrasolar *giant* planets orbit stars that are thought to be members of binary or multiple-star system (see Table 1). This surprising fact begs the question: What is the frequency of *terrestrial* planet formation in binary and multiple-star systems? A recent investigation of the effects of massive secondary companions on planetesimal dynamics led to the indentification of a previously unrecognized mode of planetesimal accretion (Kortenkamp et al. 2001). This alternative mode of accretion, dubbed Type II runaway growth, indicates that formation of terrestrial planet embryos may be facilitated by the gravitational perturbations of massive companions. In the three figures below we present a "proof of concept" based on previously published results using the Sun-Jupiter binary, which is traditionally used for initial characterizations of dynamical effects in binary systems.

Table 1: Multiple-Star Systems With Known Planets

System Name		Planets	Stars
HD142		1	2
HD3651		1	2
HD9826	(υ And)	3	2
HD13445	(Gliese 86)	1	2
HD19994	(94 Ceti)	1	2
HD22049	(ϵ Eri)	1	2
HD27442		1	2
HD40979		1	2
HD41004		1	3
HD75732	(55 Canc)	3	2
HD80606		1	2
HD89744		1	2
HD114762		1	2
HD117176	(70 Vir)	1	2
HD120136	(τ Boo)	1	2
HD121504		1	2
HD137756		1	2
HD143761	(ρ Cor Bor)	1	2
HD168443		2	2
HD178911		1	3
HD186427	(16 Cyg)	1	3
HD190360	(Gliese 777)	1	2
HD192263		1	2
HD195019		1	2
HD213240		1	2
HD217107		1	2
HD219449		1	2
HD219542		1	2
HD222404	(γ Ceph)	1	2
PSR B1620-26		1	2

Table 1: This table is compiled from Jean Schneider's Extrasolar Planets Catalog (www.obspm.fr/encycl/catalog.html) by searching the SIMBAD database (simbad.u-strasbg.fr/sim-fid.pl) for the name of each host star. Host stars that SIMBAD indicated to be members of double star catalogs are included in this table. Some host stars are not cataloged as multiples in SIMBAD, such as 55 Cancri, but are described as binaries or multiples in the planet discovery papers cited in the Extrasolar Planets Catalog. Conversely, some stars may be mistakenly cataloged as doubles, like ϵ Eri (for more on this problem see Patience et al., 2002). The on-off-on-again stellar multiplicity of Upsilon Andromedea provides an example of the problem. The SIMBAD database classifies υ And as a spectroscopic binary, although this is known to be incorrect (Morbey & Griffin 1987; Butler et al., 1997, 1999). Recently, however, Lowrance et al., (2002) found that υ And does in fact have a distant (~700 AU) stellar companion. Some of the "stars" indicated in column 3 may actually be brown dwarfs, such as in HD168443 and Gliese 86. The last entry in the table is for the planet in B1620-26, the millisecond pulsar system in the globular cluster M4. These 30 systems account for roughly one quarter of the 109 star systems with known extrasolar planets as of 27 May 2004.

Figure 1: Planetesimal Orbits for Sun-Jupiter "Binary" with Separation *D*

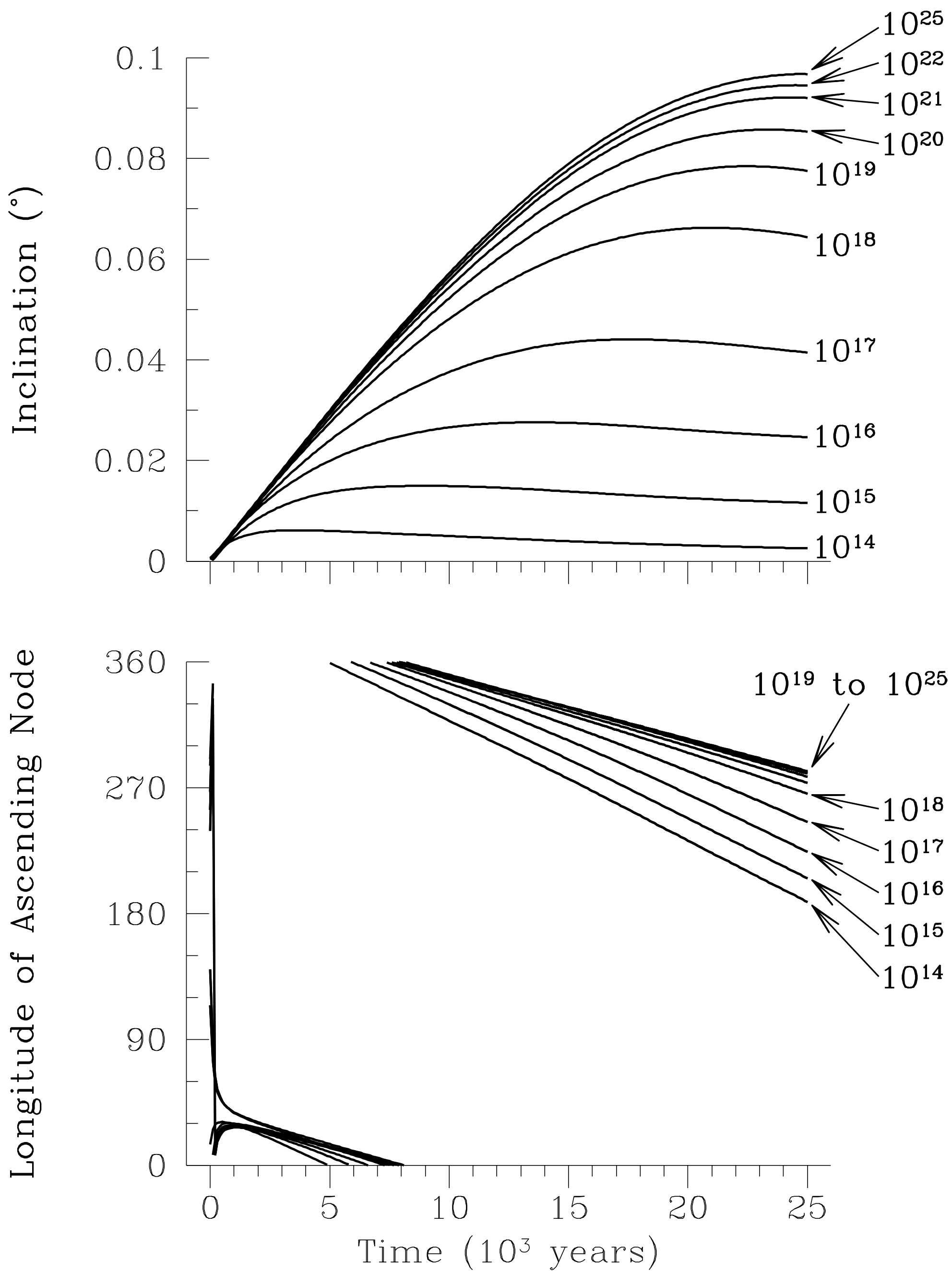
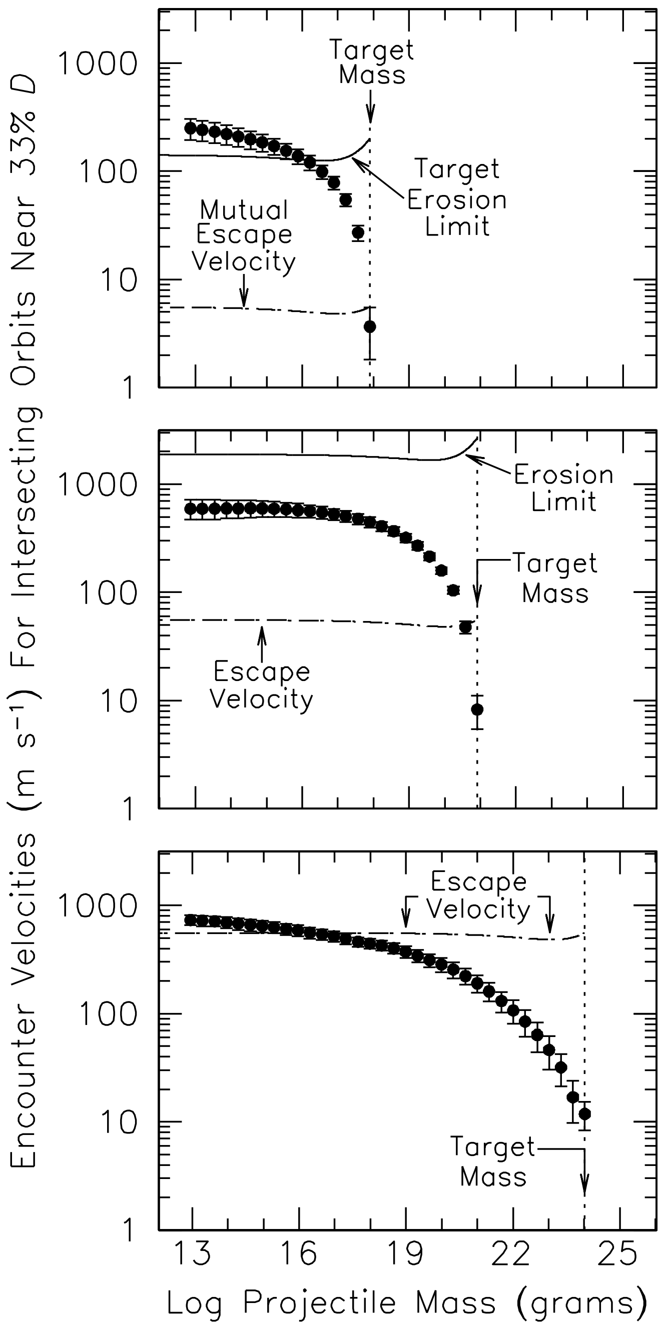


Figure 1: Orbital evolution of planetesimals in a circumsolar disk perturbed by the "companion" Jupiter at a distance *D* from the sun. Planetesimals are subject to circumsolar nebula gas drag and secular gravitational perturbations from the companion, the orbit of which is slightly inclined to the midplane of the nebula. Mutual perturbations between planetesimals are not included. Gas drag and the secular perturbations from the companion lead to size-dependent variations of inclination and longitude of ascending node for planetesimals of various mass on intersecting orbits in the habitable zone of the system. Inclinations are referred to the nebula midplane. The planetesimal mass in grams is indicated to the right of each curve. A similar size-dependency exists for evolution of eccentricity and argument of pericenter.

Figure 2: Planetesimal Velocities for Sun-Jupiter "Binary" with Separation *D*



A: Encounter velocities for 10^{18} g targets and projectiles of equal or lessor mass. Velocities above about 150 m/s lead to erosion of the target rather than growth. Only nearly equal size bodies have velocities below their mutual surface escape velocity.

B: Targets with masses of 10^{21} g are large enough that impacts of all projectiles lead to growth. However, only projectiles of nearly the same mass as the target have encounter velocities sufficiently below the mutual escape velocity to allow for significant graviational focussing.

C: Objects that grow to 10^{24} g (mass of Ceres or Vesta) have escape velocities near 500 m/s. Encounter velocities between these large planetesimals and bodies as much as 8-10 orders of magnitude smaller are below the escape velocity, allowing for significant gravitational focussing.

Figure 2: Mean encounter velocities are shown for various size planetesimals with intersecting orbits near 33% *D*, where *D* is the Sun-Jupiter separation distance. Size-dependent orbital phasing of bodies on intersecting orbits (see Figure 1 above) leads to high encounter velocities between bodies of markedly different sizes. The surface escape velocity of the combined target/projectile is shown by the horizontal dashed line. In the top two panels the erosion limit is indicated by the horisontal solid line. For encounter velocities above the erosion limit impacting projectiles crush and eject more than their own mass (crushing strength was assumed to be 10^8 ergs/g).

Figure 3: Planetesimal Growth for Sun-Jupiter "Binary" with Separation *D*

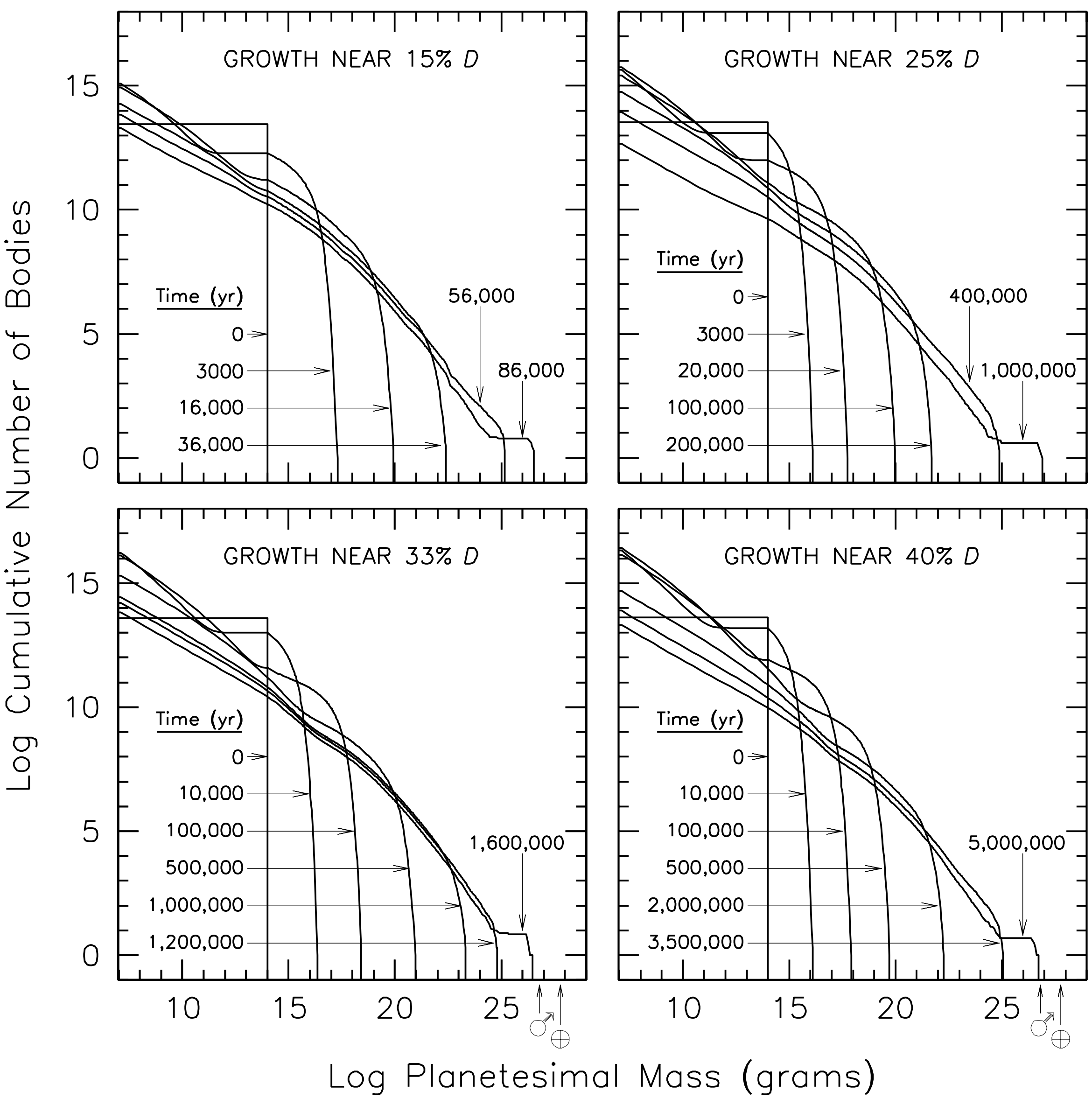


Figure 3: Growth of planetesimals in a circumsolar disk perturbed by the "companion" Jupiter at a distance *D* from the sun. The habitable zone, simply defined here as the Venus-Mars region, stretches from about 10 -25% of *D*. Initially all planetesimals have identical masses of 10^{14} grams. The initial surface density of planetesimals at 15% of *D* is 10 g cm^{-2}, scaling as $r^{-3/2}$ with heliocentric distance r. This is roughly consistent with the so-called minimum mass surface density. Collision fragments smaller than 10^{7} g (~1 meter) are presumed lost via nebular gas drag and therefore removed from the simulation. Growth is calculated in four different regions centered on 15, 25, 33, and 40% of *D*. The masses of Earth and Mars are indicated for comparison. The top two panels represent growth in the habitable zone and show initial orderly growth transitioning to Type II runaway growth of Mars-size planetary embryos in 10^{5} to 10^{6} years. Beyond the habitable zone (bottom panels) growth is slower but eventually also produces Mars-size embryos.

Future Work: Extension of Modeling to Real Multiple-Star Systems

The implication of Type II runaway growth is that terrestrial planet embryos, and thus habitable planets themselves, can form in protoplanetary disks being perturbed by massive companions. Secular perturbations and nebular gas drag act together to establish size-dependent encounter velocities that remain low when colliding bodies are of similar size. Type II runaway growth may allow planet formation to occur in binary-star systems with much tighter orbits than previously thought possible. We are currently following-up on this intriguing possibility by studying multiple-star systems already known to possess giant planets. Our objective is to develop constraints on system parameters (stellar companion masses, separations, eccentricity, even multiplicity) that will be consistent with the formation of Earth-like planets in the habitable zones around the stars in these systems.

Reference:

Kortenkamp, Wetherill, Inaba,
Runaway growth of planetary embryos facilitated by massive bodies in a protoplanetary disk.
Science **293**, 1127-1129, 2001.